A New Heat Flux Formulation Based on Effective Surface Temperatures, with Extension to the Nocturnal Boundary Layer

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Larry Mahrt and Jielun Sun

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Atmospheric Sciences
Oregon State University
Corvallis, OR 97331

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STATEMENT OF THE PROBLEM

The specific aims of the proposed research were to examine the response of the atmospheric boundary layer to surface heterogeneity and the parameterization of such influences. Here, surface heterogeneity includes both micro-scales associated with vegetation elements and scales, comparable to, and larger than the boundary-layer eddies (mesoscale surface heterogeneity). During the later part of the grant, much of the work concentrated on nocturnal boundary layer.

SUMMARY OF MOST IMPORTANT RESULTS

Through interpretation of the existing literature and analysis of new data, *Surface Heterogeneity and Vertical Structure of the Boundary Layer* has examined the vertical extent of the influence of surface heterogeneity on different horizontal scales. The influence of mesoscale heterogeneity extends vertically to levels where the spatially-averaged flux is significantly different from the surface flux. Then Monin-Obukhov similarity theory and bulk methods cannot be used to estimate the area-averaged surface flux. As a possible result, a consensus for parameterization of effective roughness lengths and transfer coefficients for heterogeneous surfaces has not emerged.

The response of boundary-layer fluxes to surface heterogeneity depends on the scale of the heterogeneity, observational height, wind speed, wind direction, boundary-layer depth and stability. In addition, ubiquitous background transient motions, sometimes associated with moving cloud patterns, influence the measured flux. Actual surface heterogeneity normally consists of simultaneous variations on more than one scale. Because of these multiple influences, simple scaling arguments can only explain a limited fraction of the variation of fluxes. Nonetheless, traditional blending height formulations are able to predict the correlation between the heat flux at level z and the surface radiation temperature; that is, predict the degree of relationship between the heat flux and the surface heterogeneity. However, the blending height formulation cannot predict the amplitude of the atmospheric response to the surface heterogeneity because: a) it does not include information on the amplitude of the surface heterogeneity and b) the amplitude of the atmospheric response is reduced by horizontal mixing due to large boundary-layer eddies that scale with the boundary-layer depth.

Traditional blending height formulations do not include information on the height of the boundary layer.

With flows over surface discontinuities, local internal boundary layers often fail to develop. When the change of surface properties is not sharp and/or of small-amplitude, the boundary layer adjusts without formation of a new internal boundary layer within the existing boundary layer. Such adjusting boundary layers exhibit significant horizontal variation of some of the higher moments, such as heat flux and temperature variance, but do not show significant horizontal variation of mean quantities. Even when local internal boundary layers do form, they normally include a thick diffuse transition layer without a sharp top. The top of the internal boundary layer is only occasionally observed as a sharp interface from instantaneous data. The top fluctuates in time so that the top of the time-averaged internal boundary layer is thick and diffuse. Over heated surfaces, the top of the internal boundary layer represents the upper limit of the thermals over the new surface and can rise quite steeply in weak wind conditions.

In *Vertical Mixing in a Partially Open Canopy,* the vertical structure of the flow in the Old Aspen canopy in the Boreal Ecosystem Atmosphere Study (BOREAS) was examined in terms of thermocouple profiles and sonic anemometers above, within, and below the aspen canopy. On clear nights, a strong surface inversion develops in the lower part of the subcanopy in contrast to more closed canopies where strong stratification does not develop. Disturbances that propagate downward through the canopy do not penetrate into the strong subcanopy surface inversion. On clear nights with weak winds, a second weaker inversion develops at the top of the aspen canopy, although mixing events easily eliminate this inversion.

On average, the subcanopy is very stable in the early evening and becomes less stable later in the evening. This appears to be due to a general increase in wind speed above the canopy during the night. However, the integrity of the surface inversion is generally maintained. On some of the nights, the stability of the flow in and above the canopy suddenly decreases in association with cold air advection. The origin of these cold fronts is not known, but they could be due to propOgation of cold air drainage from outside the area. These events generally lead to increased mixing although the details of such events vary substantially between nights. The event nature of the fluxes on some nights and the influence of advection by larger scale motions compromise the ability to estimate representative nocturnal fluxes from a single site.

The drag coefficient for the subcanopy stress exhibits a maximum at neutral stability and systematically decreases with increasing subcanopy stability. The

subcanopy drag coefficient also decreases, to a lesser extent, with increasing instability. Investigation of a number of hypotheses for this unexpected decrease with instability indicated that either the hypotheses could not account for most of the stability dependence or they could not be adequately evaluated from existing data.

The MICROFRONTS data has been analyzed in detail. In *Surface Layer Fluxes in Stable Conditions* , the scale-dependencies of the flux and flux sampling error are combined to automatically determine Reynolds turbulence cut-off time scales for computing fluxes from time series. The computed downward heat flux at the 3 m height averaged over 9 nights with 7.3 hours each night is 20% greater than the downward heat flux computed at the 10 m height. In contrast, there is only a 1.2% difference between 3 m and 10 m heat fluxes averaged over daytime periods, and there is less than a 2% difference between 3 m and 10 m momentum fluxes whether averaged over nighttime or daytime periods. This work also showed that the stability functions (nondimensional gradients) for the very stable case are less than those predicted by traditional stability functions (greater observed flux).

Aerodynamic variables are required to apply Monin-Obukhov similarity theory in the bulk formulation of surface fluxes. In the literature, these aerodynamic variables are commonly misinterpreted. *Aerodynamic Variables in the Bulk Formulation of Turbulent Fluxes* examines the concept of the aerodynamic variable, its connection to surface-layer similarity theory and how and why the aerodynamic variable is replaced with other variables.

Observed mean variables below the surface layer, such as the surface radiation temperature, or the air temperature at canopy height, are often used in place of the extrapolated aerodynamic variables in the bulk formula, requiring empirical relationships between aerodynamic and observed variables, or requiring empirical adjustments of bulk resistances. This study examined the validity of these relationships using data collected during the California Ozone Deposition Experiment (CODE). The results indicate that using a measured substitute for an aerodynamic variable can lead to significant errors in estimates of turbulent surface fluxes.

Nocturnal land breezes and daytime lake breezes are studied in *Transport of Carbon Dioxide, Water Vapor, and Ozone by Turbulence and Local Circulations*

using data collected by the Canadian Twin Otter aircraft and a deck boat which traversed Candle Lake during BOREAS. The nocturnal vertical transport of carbon dioxide, water vapor, and ozone over the lake consists of two parts: 1) mesoscale rising motion associated with land breeze convergence, and 2) significant turbulence and vertical mixing driven by buoyancy in the lower part of the internal boundary layer and shear-generation in the upper part of the internal boundary layer. For comparison, the role of the lake in the daytime is examined in terms of formation of a stable internal boundary layer due to advection of warm air from land with small carbon dioxide concentration over the cooler lake surface.

Analysis of the aircraft and boat data indicates that the nocturnal land breeze plays an important role in the regional carbon dioxide budget in the lake region. Carbon dioxide is advected horizontally by a nocturnal land breeze circulation and vented vertically over Candle Lake (``chimney effect"). Such near-surface horizontal transport implies that part of the respirated carbon dioxide never reaches the tower observational level, particularly under light wind conditions. This study speculates that preferred locations of vertical venting of carbon dioxide may also occur due to convergence of nocturnal drainage circulations or flow meandering. These circulations partly explain recent findings that tower-measured nocturnal turbulent fluxes of carbon dioxide above the canopy and the subcanopy storage of carbon dioxide frequently sum to less than the total respiration of carbon dioxide leading to ``missing" carbon dioxide.

In *Ozone Transport during the California Ozone Deposition Experiment*, the high correlation between the canopy stomatal-uptake and ozone deposition velocity is found to be strongly dominated by their diurnal variations. By averaging observed variables over the daytime periods to remove the correlations simply due to their individual diurnal variations, we found that the ozone deposition velocity is highly correlated with the buoyancy flux during the daytime. As canopy stomata are closed at night, the ozone deposition velocity is found to be related to the friction velocity. Interpretation of the derivation of the ozone deposition velocity, expressed in terms of the traditional three-resistances, is reanalyzed to explain the role of the turbulence strength in the ozone deposition velocity. We find that the resistance *rc* is the dominant resistance for the ozone deposition, not only due to the ozone uptake through biophysical processes, but also due to its role in the turbulent ozone transport.

The thermal roughness height associated with surface radiation temperature has been previously found to vary between different surface types. *Diurnal Variations of Thermal Roughness Height over a Grassland* finds that the thermal roughness height varies diurnally even over a homogeneous senescent grassland. The corresponding roughness length for momentum is relatively constant.

Both the aerodynamic temperature and the surface radiation temperature are found to be closely related to the air temperature in the middle of the grass canopy, although the aerodynamic temperature is strongly influenced by the horizontally integrated heat transfer while the surface radiation temperature represents the integrated thermal emission through the grass depth within the field of view of the radiometer. Compared to the thermal roughness length, the aerodynamic temperature is less sensitive to variations and measurement errors in sensible heat flux, wind speed, and air temperature. We find that formulating the aerodynamic temperature in terms of the surface radiation temperature is better posed for use in the bulk formula than using the surface radiation temperature directly and adjusting the thermal roughness length.

In *Nocturnal Boundary-layer Regimes*, examination of the dependence of the nocturnal boundary layer on stability suggested three regimes:

1) In the *weakly stable regime*, the heat flux increases with increasing stability due to larger temperature fluctuations. Existing similarity theory works well in this regime.
2) In the *intermediate transition regime*, the heat flux decreases with increasing stability due to restriction of the vertical velocity fluctuations by the increasing stratification. The turbulence strength, transfer coefficients and eddy diffusivities decrease rapidly with increasing stability in the transition regime. Similarity theory seems adequate for this regime but does not describe the turbulence quantities as well as for the weakly stable regime. Local scaling works better than traditional Monin-Obukhov similarity theory.
3) In the *very stable regime*, similarity theory does not adequately describe the behavior of the turbulence. Flux sampling errors are large for this regime. In addition, nonturbulent motions contribute to the variances but not the flux which obscures the relationship between variances and Monin-Obukhov scaling. That is, the variances are sensitive to choice of averaging length.

Some of the relationship between the predicted variables and z/L is due to self-correlation since both quantities are functions of u* and/or the heat flux. Monin-Obukhov similarity for scaled standard deviations performs better choosing a smaller averaging length for the very stable regime. In contrast, the residual in the surface energy balance is less when choosing a larger averaging length in order to include all of the flux. Presumably, some of the quantitative differences among existing stability functions for the very stable case are due to differences in averaging length.

Three invited survey papers were written, which became an important part of the total effort. *Stratified atmospheric boundary layers and breakdown of models* was written for fluid dynamiscists not familiar with geophysical turbulence. *Surface fluxes and boundary layer structure* surveys aspects of the unstable, neutral and stable boundary layers. *Stratified atmospheric boundary layers* was prepared in conjunction with the Stable Boundary Layer Workshop in Lovanger, Sweden in October 1997.

Participating Personnel

Larry Mahrt, Principal Investigator
Jielun Sun, Co-principal Investigator
Dean Vickers, Computer Programmer

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List of manuscripts submitted or published under ARO sponsership in referreed journals

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Sun, J. and J. Howell, 1999: Surface layer fluxes in stable conditions. To appear in *Boundary-Layer Meteorol.*.

Sun, J. and W. Massman, 1999: Ozone transport during the California Ozone deposition experiment. To appear in *J. Geophys. Res.*.

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Larry Mahrt and Jielun Sun

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Corvallis, OR 97331

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13. ABSTRACT *(Maximum 200 words)*
The state of the art concepts of the influence of surface heterogeneity on the atmospheric boundary layer are studied using several new data sets. This analysis shows that the internal boundary-layer theory is valid only with sharp well-defined surface changes. With more typical surface heterogeneity and with very stable conditions, the concept and models of the internal boundary layer do not apply. The concepts of the thermal roughness length and areodynamic variables are also found to fail, or behave in an undeterminable complex manner, over both modest and strong surface heterogeneity including microscale heterogeneity associated with complex vegetation and tall partially open canopies. Generalized formulations and new approaches are suggested.

With very stable conditions, similarity theory breaks down and the concept of the boundary layer is challenged. The primary source of the turbulence may originate from elevated semi-detached shear layers and surface-based similarity theory fails to describe even the flux-gradient relationship near the surface. While we have modified similarity theory to better parameterize surface fluxes in very stable conditions, major uncertainties remain.

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